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Erasing a Gender Gap in Performance in a Multidisciplinary Introductory Engineering Course

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Abstract
This paper will discuss the transition from a lecture-based multidisciplinary introductory engineering course to a revised version that integrates theory and hands-on practice around a theme of underwater robotics, including discussion of the design, implementation, and evaluation of the revised course. The course is required for all students (including non-engineering majors) at a small liberal arts college and is the first engineering course for the majority of enrollees. Final grades in the original lecture-based course showed a gender disparity in which male students outperformed female students that had persisted over the course of many offerings. By employing best practices in engineering education, with a special focus on inclusive teaching practices, the course was revised to a model that includes active learning (flipped classroom) tutorials and hands-on practicums. Students attend two tutorial sessions and one hands-on practicum session each week. Before the first tutorial session each week, students watch videos created by the instructors. Students take individual and team quizzes (following the procedure used in Team-Based Learning), which provide accountability for learning the course material. With the remaining time in the first tutorial of the week and the entirety of the second tutorial of the week, students work in small groups with significant student-instructor interaction on context-rich problems focused on real-world engineering applications. The students then take part in a 2.5-hour practicum session where they interacted with physical manifestations of the course content, largely focused around an underwater robot. For example, in one practicum the students placed their robot in a water tank with a buoyancy "spring" attached, then introduced a step input in motor force and measured the robot's step response; they then used the output data to find the robot's damping ratio and natural frequency.

Mastery of course content was measured in both the original lecture-based course and the revised course via a pre/post content test; other evaluation measures included a pre/post attitudinal survey regarding the usefulness of class content, intent to major in engineering, and understanding of the engineering profession and student evaluations of teaching. The results show a significant increase in learning and affective gains for all students. Furthermore, the gender disparity in final course grades has disappeared in the revised course and there is no difference between the performance of male and female students on the pre/post content test.

Background
At Harvey Mudd College, all students, including non-engineering majors, are required to take a multidisciplinary introductory course in engineering titled Introduction to Engineering Systems. For many years, this course had been taught in a standard lecture format, with two large (~ 225 student) 75-minute lectures and one smaller (~25 student) 50-minute recitation section per week. Unfortunately, a gender disparity in final grades for the course in which female students underperformed relative to male students[1] persisted over several years (see Figure 1). Although

[1] Due to the existing data set, this paper is focused on binary gender. We hope that future studies will allow for the study of non-binary gender as well.

this gap was not always statistically significant, it was nonetheless cause for concern. Furthermore, engineering faculty were concerned that - beyond the gender gap - the course produced less learning and understanding of the engineering field and major than desired, and they perceived that both students and faculty from other departments on campus under-valued the course.

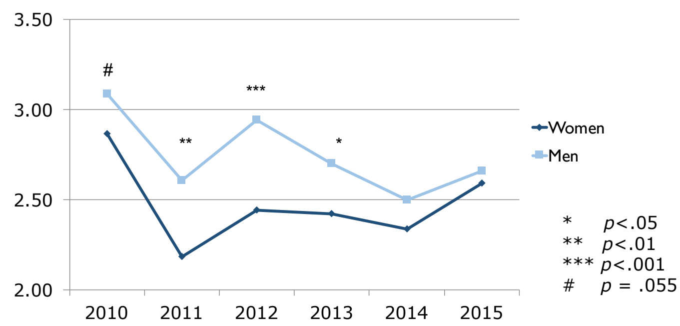


Figure 1: Average final grade (out of 4.0) in the original course by gender.

Redesigned Course Outcomes

The course was redesigned in a two-year process involving extensive surveying of alumni, discussions with other departments on campus, and focus groups with current engineering faculty and students; a more detailed discussion of this process can be found in Lape et al. [1]. Feedback from all of the stakeholders led to the generation of desired outcomes for the new course, shown below.

Desired Outcomes

For a diverse student body, including both engineering majors and non-engineering majors and students from underrepresented groups,

1. Increase engagement in a rigorous engineering course.
2. Increase utility of a rigorous engineering course.
3. Increase student learning in a rigorous engineering course
4. Increase student understanding of the engineering field and major.
5. Maintain (or decrease) student workload.

A series of design alternatives for the revised course were generated and evaluated based on these outcomes and associated objectives and constraints. The design alternative that the engineering faculty supported as the best match to these outcomes, objectives, and constraints was a course centered around experiential learning that combined classroom practice in theory and hands-on practicum sessions.

Experiential Learning: Theoretical Framework

The main theoretical framework supporting the course redesign was Kolb's Experiential Learning Theory (ELT). ELT is centered on a learning cycle composed of concrete experience, reflective observation, abstract conceptualization, and active experimentation (see Figure 2) [2], [3]. Our high-level course design aimed to not only move students through this cycle, but to

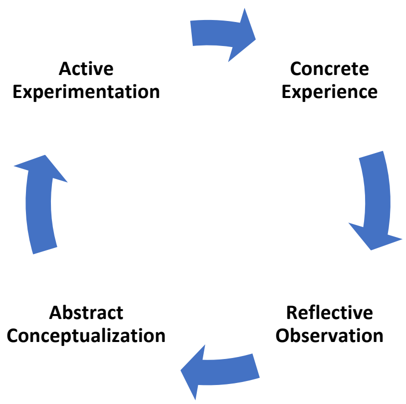


Figure 2: Kolb's Experiential Learning Theory cycle

do so repeatedly. When introducing new material, students were asked to recall previous concrete experiences and reflect on these experiences (when reasonable). They then learned and interacted with engineering theory related to those experiences, and finally experimented with that theory in the hands-on practicum. We could then use the practicum itself as the basis for another set of concrete experiences and therefore another round through the cycle, often in the form of homework problems related to the practicum (see next section for details).

Evidence-Based Pedagogy Employed in Course Redesign

At the detailed design level, we employed a wide variety of evidence-based pedagogical techniques, several of which could be considered inclusive teaching techniques. First, we infused the entire course with active learning, both in the form of the practicum activities and the entirely active learning tutorial activities (see details in the following section). Based on Freemen et al.'s meta-analysis of 225 studies[4] which, amongst other findings, showed that active learning increases student performance on examinations and concept inventories by 0.47 SDs as compared to students taught using traditional lecturing, we believe (and Freemen et al. suggested as well) that active learning should be the baseline for further pedagogical innovation.

Next, we incorporated many aspects of a collaborative, problem-based learning method known as team-based learning (TBL) [5]. In TBL, course material is presented as a series of modules. For each module, students prepare outside of class meeting time by reading or watching videos, then take in-class individual and team quizzes on the material. The remainder of the module is spent solving application-focused exercises in teams. Studies have shown that TBL has the ability to increase learning for all students, and in particular for lower-performing students [6], [7]. We also designed the new course such that the individual and team testing occurred each week (rather than less frequently) based on research showing that frequent testing improves student learning [8] and reduces achievement gaps between over- and under-represented groups [9].

Overall, we sought to provide a highly-structured course design with active learning, high engagement levels, and frequent low- or no-stakes testing, since this combination of pedagogical tools has been shown to raise the performance of all students, with disproportionate benefits for underrepresented minorities [10], [11].

Redesigned Course Structure
The ELT cycling and evidence-based practices discussed above where implemented via the use of instructor-made videos, quiz tutorials, problem tutorials, practicums and homework. The weekly format is shown in Table 1 below. Students attended two 50-minute tutorials and one 2.5-hour practicum session each week. Before the first tutorial session of the week, students watched a set of instructor-made videos. This was the sole mode of new content delivery, making this a flipped classroom format. Flipped classrooms have been shown to be equally effective as other active learning methods [12], and allowed for 1) the use of class time for active, team-based and hands-on learning without sacrificing content, and 2) the use of small (30-35 student) tutorial sections staffed by multiple instructors (two professors and one undergraduate assistant) rather than one simultaneous meeting in a large lecture hall.

The first course meeting of the week was dedicated to a multiple-choice quiz taken individually, then as a 5- to 6-person team, as done in TBL. Instructors then answered questions from the quizzes and videos; the remainder of the class meeting time was spent solving problems in teams. The second tutorial meeting focused on context-rich tutorial problems, solved in smaller teams (3-4) with frequent instructor interaction. These problems were meant to be challenging and rooted in practical STEM contexts, and covered a wide range of engineering, physics, chemistry and biology disciplines; students analyzed systems from skin (as a viscoelastic material), to circuits on the underwater robots, to control of anesthesia dosing. The problems on homework sets were of the same nature as these context-rich, multidisciplinary tutorial problems, and most homework sets contained at least one problem that directly tied to the either the current or a previous practicum.

Deadline	Task
before Monday	Watch assigned instructional videos
Monday Tutorial	Individual and Team quiz on video topics Brief tutorial problems
Wednesday Tutorial	Context-rich tutorial problems Problem set due
Wed – Fri	Practicum

Table 1: Weekly course structure of redesigned course

After both tutorial meetings had taken place each week, students attended a practicum session in which they applied the theory learned in the videos and tutorial sessions to a physical engineering system; topical connections between the tutorial module and practicums are shown in Figure 3. As previously mentioned, the practicum moved students through the ELT cycle, and gave them further concrete experiences with the course material. As a majority of the students were inexperienced with the techniques required to carry out the experimental work (e.g. using an oscilloscope, soldering), the manuals gave clear instructions for many procedural tasks, while giving students less explicit instruction on how to complete the conceptual tasks such as using theory to model or predict the experimental results (for a sample practicum manual, see [1]). Additionally, to allow students to focus on the concepts and reduce disparity between more- and less-experienced students, students were scored mainly on the effort put forth during the practicum session: working steadily throughout the practicum session, not completion of all tasks, resulted in a full score. As mentioned above, many homework sets contained a problem that required data from the practicum to reinforce the connection between theory and practice.

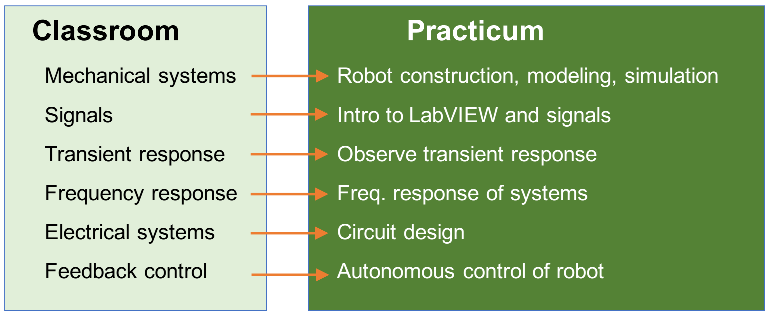


Figure 3: Correspondence between content in classroom sessions and practicum sessions.

The course was also designed such that the topics and practicums built on each other up to a culminating experience. Students began the semester by building an underwater robot, spent subsequent weeks learning about mechanical models for the robot, building circuits and learning about the electrical models for those circuits, and learning about control theory that they eventually implemented to control the robot. In the final practicum of the semester, students brought their completed robot and LabVIEW code with their chosen control constants to a nearby lake, where their robots autonomously moved to desired depth and collected temperature measurements at that depth.

One final note regarding the course redesign: while the course content was largely consistent across the original and revised course, some changes were made during the redesign. In particular, feedback control was added, the use of Laplace transforms replaced the use of Fourier transforms, and coverage of signal representation was drastically reduced (the full set of learning outcomes for the original and revised course, as well as the modules in each version, are available in [1]).

Evaluation Methods

The performance of the original course as offered in Fall 2015 was compared to the revised course offered in Fall 2016, with the course outcomes serving as the basis for evaluation; the evaluation methods used to measure these outcomes are summarized in Table 2 below. Six of the seven instructors were the same for both offerings, so instructor effects on performance and attitudes should be negligible.

Evaluation Outcome	Method
Increase engagement in a rigorous engineering course.	Pre/post survey Student Evaluations of Teaching (SET)
Increase utility of a rigorous engineering.	Pre/post survey SET
Increase student learning in a rigorous engineering course	Pre/post test Final grades (for gender comparison only) SET
Increase student understanding of the engineering field and major.	Pre/post survey
Maintain (or decrease) student workload.	SET

Table 2: Evaluation outcomes and methods

The pre/post test to measure student learning was comprised of two long-answer problems, one focused on the frequency response of a mechanical system and the other on the transient response of an electrical system; these tests were scored by teaching assistants. Quantitative survey measures were analyzed in aggregate and as matched pre/post pairs for those students who responded to both surveys. To reduce bias, qualitative responses were examined for themes by Dr. Laura Palucki Blake, a trained social scientist who was not a course instructor. Additionally, reflective feedback from instructors was collected after the end of the Fall 2016 semester and instructor contact hours were counted and compared to those in other courses. This paper will focus on quantitative survey results, pre/post test results, and final course grades because these measures were examined by gender; results for the other measures are reported elsewhere [1].

Sample Population

Approximately 200 students completed the course in each of the two semesters reported on here, with between 37 and 84% participation in the evaluation measures (details in Table 3 below). The sample population was generally representative of the full course population overall, with a slight underrepresentation of female students in the survey data relative to the course population in Fall 2015 and a slight overrepresentation of female students relative to the course population in Fall 2016 (see Figure 4).

	Original (Fall 2015)	Revised (Fall 2016)
N, Entire course	205	216
N, Matched pair survey respondents	76 (37%)	110 (51%)
N, Post-tests submitted	118 (58%)	182 (84%)

Table 3: Course and sample population

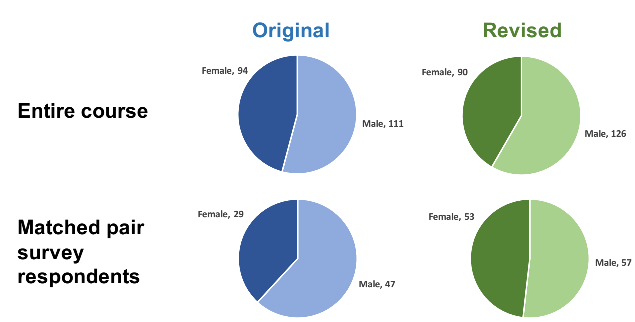


Figure 4: Course and sample population by gender

Results and Discussion

As mentioned above, this discussion will focus on results by gender; evaluation measures for the course as a whole can be found in [1]. However, we will begin the discussion by noting that learning markedly improved with the course redesign, as measured by the pre/post test used in both the original and revised course (Figure 5). Because we were unable to discern whether some scores of zeros were due to lack of submission or due to a student's inability to complete the problem, the data set was analyzed both with and without scores of zero. In either case, a large and statistically significant increase in post-test score was observed and, as can be observed in the distribution, the lower-performing end of the class shifted upwards.

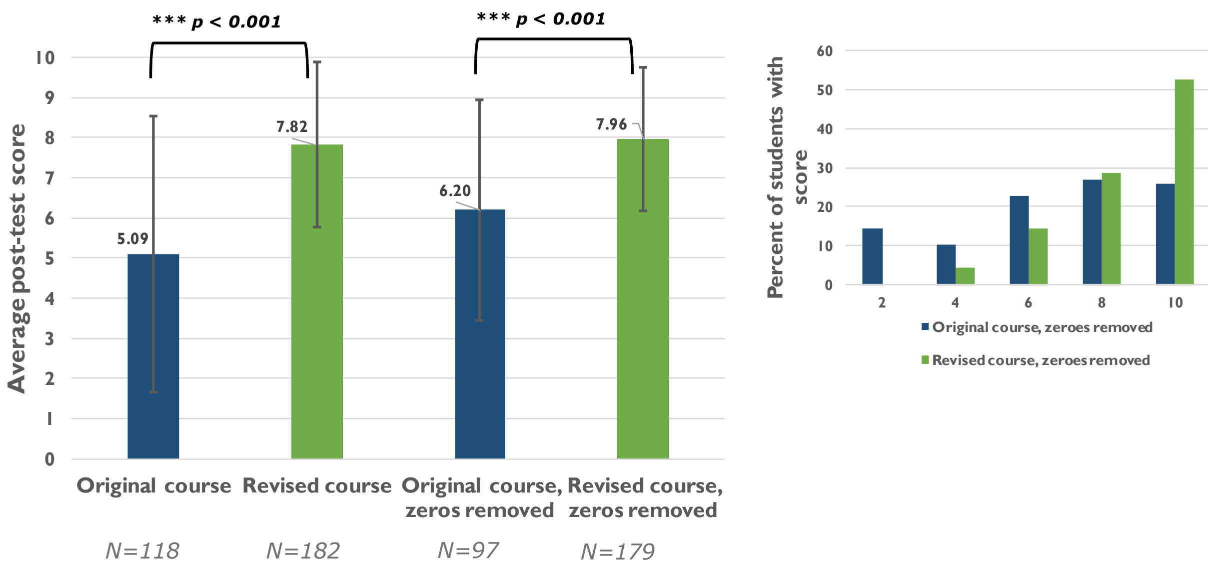


Figure 5: Performance on post-test in original and revised course in aggregate (left) and as a distribution (right).

Moving to examining course performance by gender, Figure 6 shows that the gender gap observed in the original course grades (shown in Figure 1) is no longer observed in the revised course grades: the average score for male and female students are nearly identical, with a slightly tighter distribution for women than men.

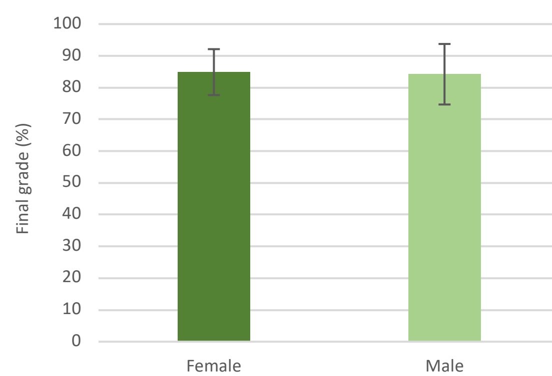


Figure 6: Final grade (as a percentage of total possible points) in the revised course by gender.

The average post-test scores by gender for the original and revised courses are shown in Figure 7. While there is no statistically significant difference between the performance of men and women in either the original or the revised course, the average score for women is lower than that for men in the original course and virtually the same as men in the revised course. The distributions of scores by gender, shown in Figure 8, shows a somewhat bimodal distribution of scores for women in the original course, with a lower-performing group and a higher-performing group. In the revised course, the number of female students receiving a given score increases (nearly) monotonically as the score increases (which is also true of the male students). These data confirm the oft-repeated notion that inclusive teaching practices improve the performance of all students in the course, with a disproportionate increase in performance for underrepresented groups.

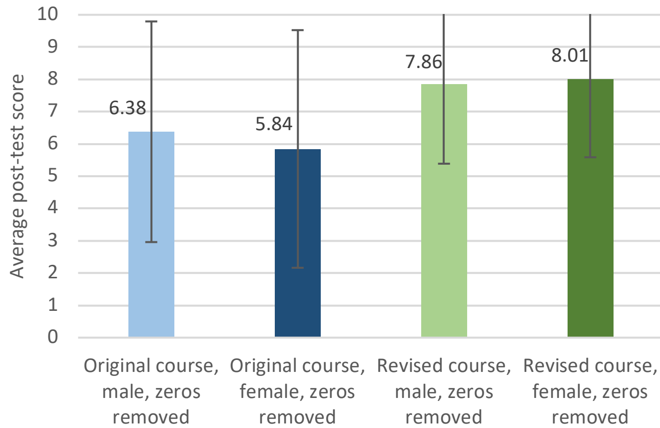
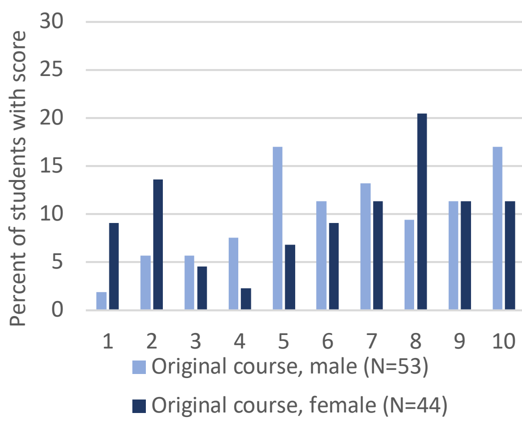


Figure 7: Average post-test scores for male and female students in the original and revised course.



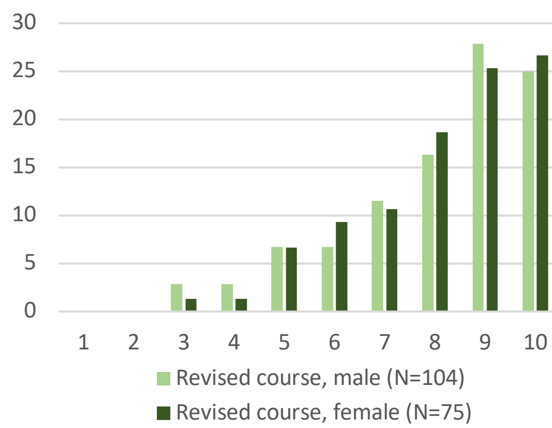
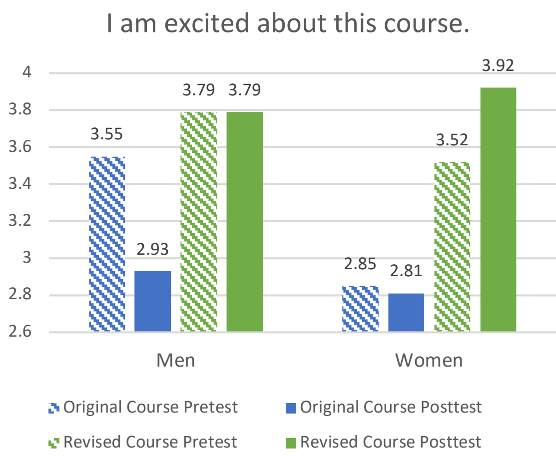
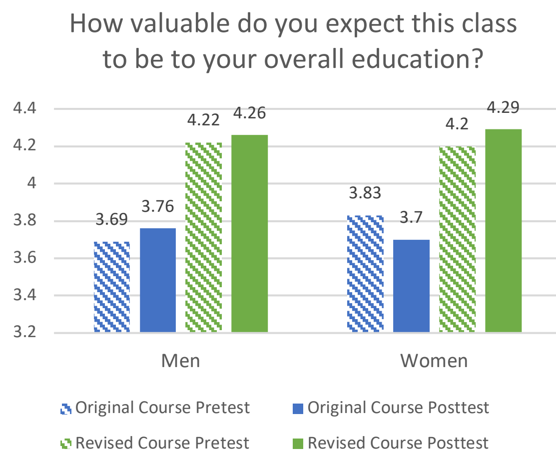
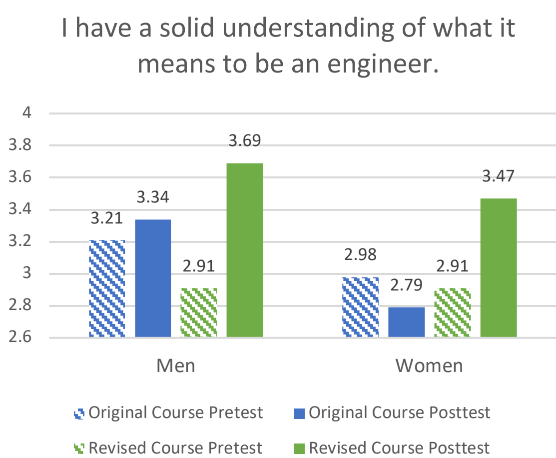


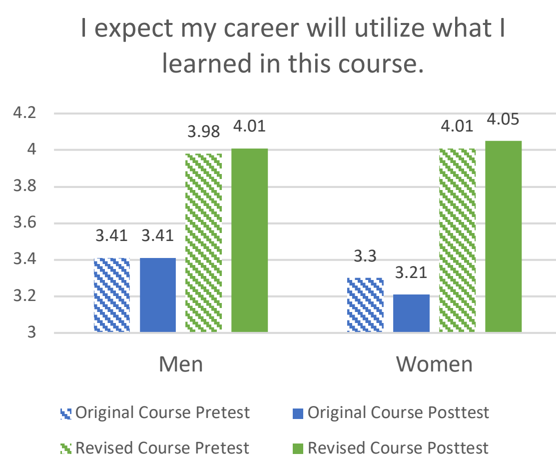
Figure 8: Post-test score distributions for the original course (left) and revised course (right) by gender.

Pre/post survey results also showed differences by gender between the original and revised courses. Figure 9 shows the 5-point Likert scale (strongly disagree to strongly agree for most but not all items) responses to the survey items "I am excited about this course.", "How valuable do you expect this course to be to your overall education?", "I have a solid understand of what it means to be an engineer.", "I expect my career will utilize what I learned in this course." and "I see how engineering concepts apply and can be used in other disciplines." Notably, in the original course, women gave a lower rating to all survey items in the post-test than in the pre-test on average with the exception of "I see how engineering concepts









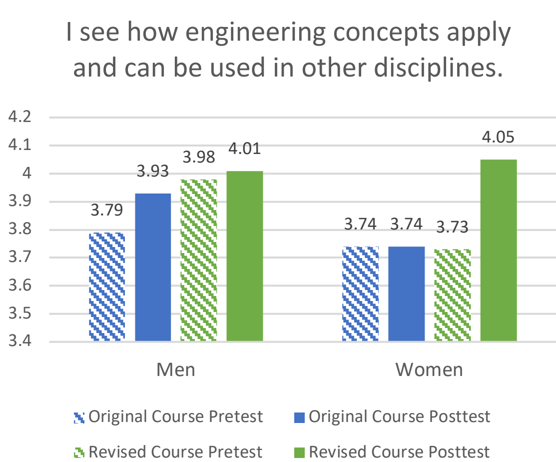


Figure 9: Pre/post survey results for the original and revised course by gender. Survey items used a 5-point Likert scale.

apply and can be used in other disciplines.", while in the revised course they gave higher ratings to the survey items in the post-test than in the pre-test. Male-identified students, on the other hand, showed increases from pre- to post-course surveys in both the original and revised courses, with the exception of the item "I am excited about this course." This means that women felt decreased excitement, feeling of value, understanding of engineering, and feeling of course usefulness as a result of the original course, whereas men only felt a decrease in excitement and felt increases in the other areas. The only statistically significant difference in response on any item (for pre- and post-course surveys in either version of the course) by gender was in the original course posttest rating of "I have a solid understanding of what it means to be an engineer." (men rated this higher with $p < 0.05$). However, the *increases* in matched pair responses from pre- to post-test in the revised course were statistically significant for both men and women on the item "I have a solid understanding of what it means to be an engineer." ($p < 0.001$ for both genders); for women only on the items "I am excited about this course." ($p < 0.1$) and "I see how engineering concepts apply and can be used in other disciplines." ($p < 0.5$); and for men only on the item "How valuable do you expect this course to be to your overall education?" ($p < 0.5$).

Conclusions and Future Work

A required engineering course was revised from a traditional lecture-based course to a highly structured, highly interactive hands-on course that incorporated several best practices in STEM education. Based on the data collected in this work, the revised course has improved learning and shown affective gains for all students as compared to the original course, with a disproportionate gain by female students. Given the large number of pedagogical tools and methods employed in the course redesign, it would not be possible to isolate a single tool or method that might cause the observed improvement or even the majority of the observed improvement. Regardless, these results support the adoption of inclusive teaching pedagogy by instructors, particularly in courses where gender disparity in performance has been observed.

In the future, we hope to examine the performance and affective of underrepresented minorities in STEM in this course. We also plan to analyze data from the second offering of the revised course to make sure that the improvements observed here persist. [Note to reviewers: 2017 data should be available in time for the presentation and possibly even the final draft of this paper].

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